previous fragmentation processes, it is likely that the HCN^+ formation, which has no reverse activation barrier, probably is another m/z 54 dissociation channel with, of course, no kinetic energy release in the dissociation.

V. Conclusions

We have studied the photon selection of the *s*-tetrazine ion chemistry using synchrotron radiation in the 9–22 eV energy range. The *s*-tetrazine parent ion is found to dissociate at internal energies lower than the first excited state. This is reminiscent of the dissociation of the neutral molecule below the S_1 onset. In contrast to neutral *s*-tetrazine, the lowest parent ion dissociation path is to two fragments, $N_2 + C_2N_2H_2^+$, with an activation energy of 0.96 eV (at 10.2 eV photon energy). Calculations of relative stabilities of $C_2N_2H_2^+$ isomers would help in positively identifying the structure of this $C_2N_2H_2^+$ fragment. The loss of CN from $C_2N_2H_2^+$ is found to explain the further appearance of m/z 28 at 10.5 eV, which is identified as $HCNH^+$ and not N_2^+ (from thermochemistry). HCN^+ is found to appear at its thermodynamical limit around 11.4 eV. The overall fragmentation of *s*-tetrazine ion involves the formation of $N_2 + CN + HCNH^+$ via sequential dissociation steps (Figure 4). The nature of the process and products contrasts that of the neutral molecule case. This is probably because the large proton affinity of HCN favors the formation of $HCNH^+ + CN + N_2$ rather than $HCN + HCN^+ + N_2$ or $N_2^+ + 2HCN$, which requires higher internal energies.

Further investigation of the kinetic energy release and the rate constants of these dissociation pathways should provide further details of the steps involved, especially in cases where the reverse activation barriers are large. We plan further studies of the neutral fragmentation and ion kinetic energy distributions.

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Stereochemical Effects in the Gas-Phase Pinacol Rearrangement. 2. Ring Contraction versus Methyl Migration in *cis*- and *trans*-1,2-Dimethylcyclohexane-1,2-diol

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Abstract: The gas-phase pinacol rearrangement of *cis*- and *trans*-1,2-dimethylcyclohexane-1,2-diols, promoted by D_3^+, $CH_5^+/C_2H_5^+$ and $t\text{-}C_4H_9^+$ ions, was studied by mass spectrometric and radiolytic methods in the pressure range 0.5–760 Torr. When product isomerization is inhibited, by using $N(CH_3)_3$ as a trapping reagent at high pressure, mixtures of 2,2-dimethylcyclohexanone and 1-acetyl-1-methylcyclopentane were recovered from the reaction. In methane, the trend of the measured relative rates for ring contraction (k_5), methyl or hydroxyl group migration (k_6) versus the rearrangement rate of pinacol itself (k_p), is $k_6(trans) \simeq k_5(trans) \geqslant k_5(cis) > k_6(cis) \geqslant k_p$. No evidence for the formation of an intermediate carbenium ion was found. Stereochemical aspects of the mechanism are discussed and compared with solution data.

The combined application of mass spectrometric and radiolytic techniques was recently exploited to investigate the pinacol rearrangement of 1,2-dimethylcyclopentane-1,2-diols, promoted by gaseous Brønsted acids, and to show how the stereochemistry of the starting glycol influences the rate of the reaction.[1] In particular, methyl group participation in the rate-limiting loss of a water molecule was shown to take place in the cis epimer, which rearranges faster than the trans one to 2,2-dimethylcyclopentanone.

The study of the pinacol rearrangement in a gaseous environment allows one to follow the evolution of the protonated substrate along the reaction coordinate, in the absence of strong solvation interactions with the medium and competitive isomerization processes, thus displaying some stereochemical aspects which do not show up in solution experiments. This prompted us to extend the investigation to the rearrangement of 1,2-dimethylcyclohexane-1,2-diols (**1**), where the interplay of the stereochemistry of the reacting centers and the conformation of the substrates could help understanding the overall picture of the reaction mechanism.

The same reaction was studied in solution ($H_2O/HClO_4$),[2,3] where *cis*- and *trans*-**1** both gave some 2,2-dimethylcyclohexanone (**2**) together with predominant amounts of 1-acetyl-1-methylcyclopentane (**3**). The rearrangement is accompanied by isomerization of one diol to the other and ^{18}O exchange with the solvent. The data supported an A-1 mechanism and a common carbenium

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Table I. CID/MIKE Spectra[a] of the m/z 127 Ions from the Dehydration of Protonated *cis-* and *trans-*1,2-Dimethylcyclohexane-1,2-diol (**1**) or the Protonation of 2,2-Dimethylcyclohexanone (**2**), 1-Acetyl-1-methylcyclopentane (**3**), and 1,2-Dimethyl-1,2-epoxycyclohexane (**4**)

	cis-**1**		*trans*-**1**		**2**		**3**	**4**
m/z[b]	CH_4	i-C_4H_{10}	CH_4	i-C_4H_{10}	CH_4	i-C_4H_{10}	i-C_4H_{10}	i-C_4H_{10}
111	4.1	4.7	4.5	5.4	4.7	7.0	5.1	5.0
97	2.7	2.6	2.7	2.4	2.9	3.5	3.0	2.8
85	5.9	8.1	6.1	8.1	5.2	3.5	8.2	6.2
69	8.2	7.0	8.5	7.0	8.7	7.9	7.2	7.5
67	7.3	7.5	7.0	7.5	7.5	7.9	7.9	7.8
57	4.2	3.9	3.8	3.3	3.2	2.8	3.1	2.8
55	7.7	9.5	7.6	9.9	8.2	11.3	9.5	9.9
53	3.1	3.3	3.5	3.2	2.7	3.7	3.5	3.2
43	36.0	29.2	35.7	28.7	35.6	24.5	28.8	30.5
41	9.5	11.3	9.5	11.9	10.2	13.1	10.9	11.9
39	5.8	6.8	6.1	7.1	5.7	7.9	6.6	6.6
29	2.2	2.6	2.5	2.2	2.4	2.9	2.8	2.6
27	3.0	3.3	2.6	3.4	2.9	3.8	3.4	3.2

[a] Relative intensities as percent of the total fragment ion abundances. The data are the average of at least three independent runs, each representing the accumulation of 30 consecutive scans. Standard deviation ca. 15%. [b] Peaks at m/z 109, 83, and 59 contain contributions from unimolecular fragmentation processes and therefore have been omitted.

intermediate was assumed for both glycols.[3]

The problems in understanding the mechanism of the pinacol rearrangement in solution,[4] and those inherent with its stereochemical requirements for the specific case at issue,[5] were already thoroughly illustrated.

On the other hand, the behavior of closely related cyclic diols was studied in the gas phase by mass spectrometry under chemical ionization (CI) conditions, employing methane or isobutane as the reactant gas, and the occurrence of skeletal rearrangement via protonation and loss of a water molecule was experimentally characterized by collisional activation spectroscopy of the relevant product ions.[6-8]

The present paper is aimed at studying the course of the gas-phase pinacol rearrangement of **1** both over a wide pressure range, i.e., from 10^{-2} to 760 Torr, and with use of different Brønsted acids, in order to vary the internal energy of the protonated glycol and to select the best experimental conditions for evaluating the branching ratio of competitive paths, e.g., ring contraction versus methyl or OH migration.

Experimental Section

Materials. Deuterium, methane, isobutane, oxygen, and trimethylamine were high purity gases from Matheson Co., used without further purification.

trans-1,2-Dimethyl-1,2-cyclohexanediol (*trans*-**1**) was prepared from 1,2-dimethylcyclohexene (K&K) and peroxyformic acid;[9] the crude diol, obtained after treatment with periodic acid, was recrystallized from hexane (mp 92–93 °C).

cis-1,2-Dimethyl-1,2-cyclohexanediol (*cis*-**1**) was synthesized by hydroxylation of 1,2-dimethylcyclohexene with osmium tetroxide.[10] The product obtained by distillation (bp_{10} 102 °C) was purified by recrystallization from pentane (mp 49–50 °C).

1-Acetyl-1-methylcyclopentane (**3**) was obtained by the method of Meerwein[11] (bp_{10} 53 °C; semicarbazone mp 141 °C).

2,2-Dimethylcyclohexanone (**2**) was prepared by methylation of 2-methylcyclohexanone (Fluka) (bp_{100} 101 °C; semicarbazone bp 200 °C).[12] 1,2-Dimethyl-1,2-epoxycyclohexane (**4**) was prepared from the olefin and *m*-chloroperbenzoic acid;[13] the crude product was distilled through a glass-bed packed column (bp_{10} 35 °C) and purified by GLC on a 5-m long column packed with 10% Carbowax, 2% KOH on 60–80 mesh Chromosorb W. Tetramethylene glycol and methyl *tert*-butyl ketone were research grade chemicals from Fluka. The starting materials, suitably purified, were checked by GLC, by using the same conditions employed for the analysis of the reaction products.

Unless otherwise stated, the procedures for the preparation of the radiolytic samples were those previously reported.[1] The irradiations were carried out at 37 °C in a 220 Gammacell from Nuclear Canada Ltd., to a dose of ca. 2×10^4 Gy at a rate of ca. 10^4 Gy h^{-1}.

The analysis of the irradiated mixtures was carried out on a Hewlett-Packard Model 5730A gas chromatograph, equipped with a FID detector on the following columns: (1) 8 ft × $^1/_4$ in. glass column packed with 5% FFAP on Chromosorb G AW-DMCS 80–100 mesh operated at 60–210 °C and (2) 25 m × 0.20 mm Carbowax 20M ULTRA performance capillary column, operated at 140 °C.

The products were identified by comparison of their retention volumes with those of authentic samples and their identity confirmed by GLC–MS (Hewlett-Packard Model 5982A). The yields were measured from the area of the corresponding elution peaks, by using individual calibration factors.

The mass analyzed ion kinetic energy (MIKES) and the collision-induced dissociation (CID) spectra were recorded on a VG-Micromass ZAB-2F mass spectrometer equipped with a combined EI/CI source and a VG-11/250 Data System. The spectra represent the average of at least 30 consecutive scans and were collected under the following conditions: source temperature, 150 °C; emission current, 1 mA; electron energy, 100 eV; repeller voltage, 0 V; reactant gas pressure (CH_4 or i-C_4H_{10}) 0.5 Torr, as directly measured with a MKS Baratron Type 221-A manometer. The CID spectra were obtained by introducing He in the collision gas cell located in the second field-free region (FFR) of the instrument until the parent ion intensity was reduced to 30% of its value and by scanning the voltage of the electrostatic analyzer. The instrument was tuned at 2000 mass resolution and 5000 fwhm energy resolution, with an accelerating voltage of 8 kV.

Results

Mass Spectrometry. Protonation under CI conditions of *cis*- and *trans*-**1**, by the gaseous Brønsted acids formed in i-C_4H_{10} or CH_4 plasma, namely t-$C_4H_9^+$ and $C_nH_5^+$ (n = 1, 2) ions, respectively, produced an abundant m/z 127 peak corresponding to loss of a water molecule from the $M + H^+$ ions. Proton transfer to 2,2-dimethylcyclohexanone (**2**), 1-acetyl-1-methylcyclopentane (**3**), and 1,2-dimethyl-1,2-epoxycyclohexane (4) as well, yielded species with the same m/z ratio.

These ions undergo metastable unimolecular decomposition in the second FFR of the instrument, giving MIKES spectra characterized by an abundant m/z 109 fragment, together with minor peaks at m/z 83 and 59, whose relative intensities were not significantly different for the various precursors employed.

The nondecomposing population of the m/z 127 ions was therefore assayed by CID spectrometry, by using He gas in the cell located near the first collector of the instrument.

The relevant spectra are reported in Table I, where the peaks at m/z 109, 83, and 59 are omitted owing to possible contribution from unimolecular processes.

Table II displays the correlation coefficients, taken as an estimate of similarity among the spectra,[14] from the linear regression

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Table II. Correlation Coefficients of CID/MIKE Spectra of the *m/z* 127 Ion

	$i\text{-}C_4H_{10}$				CH_4		
	trans-**1**	**2**	**3**	**4**	*cis*-**1**	*trans*-**1**	**2**
$i\text{-}C_4H_{10}$							
cis-**1**	0.998	0.952	0.999	0.995	0.984	0.985	0.986
trans-**1**		0.962	0.998	0.996	0.975	0.977	0.980
2			0.954	0.973	0.929	0.932	0.970
3				0.996	0.983	0.985	0.987
4					0.984	0.986	0.991
CH_4							
cis-**1**						0.999	0.998
trans-**1**							0.998

Table III. Products from the Protonation of *cis*- and *trans*-1,2-Dimethylcyclohexane-1,2-diol (**1**) by Gaseous Acids[a]

system composition (Torr)[b]				rel yield of products (%)	
bulk gas	$N(CH_3)_3$	substrate	G_M[c]	**2**	**3**
D_2, 760		*cis*-**1**, 7.1×10^{-2}	0.7	9	91
D_2, 760	3	*cis*-**1**, 8.0×10^{-2}	0.2	62	38
D_2, 100		*cis*-**1**, 7.7×10^{-2}	2.7	18	82
D_2, 760		*trans*-**1**, 7.3×10^{-2}	0.3	23	77
D_2, 760	3	*trans*-**1**, 7.1×10^{-2}	0.1	55	45
D_2, 100		*trans*-**1**, 7.0×10^{-2}	2.3	26	74
CH_4, 760		*cis*-**1**, 7.0×10^{-2}	0.3	4	96
CH_4, 760	3	*cis*-**1**, 7.1×10^{-2}	0.1	16	84
CH_4, 100		*cis*-**1**, 5.7×10^{-2}	2.5	9	91
CH_4, 760		*trans*-**1**, 6.7×10^{-2}	0.4	17	83
CH_4, 760	3	*trans*-**1**, 7.9×10^{-2}	0.2	39	61
CH_4, 100		*trans*-**1**, 6.4×10^{-2}	2.1	23	77
neo-C_5H_{12}, 760		*cis*-**1**, 7.3×10^{-2}	0.02		100
neo-C_5H_{12}. 760		*trans*-**1**, 7.7×10^{-2}	0.02		100

[a] D_3^+ from the radiolysis of D_2 and $C_nH_5^+$ ($n = 1, 2$) from CH_4. [b] O_2 (5 Torr) was present in all systems as radical scavenger. [c] Number of molecules formed per 100 eV absorbed energy. Standard deviation ca. 10%. See text.

Table IV. Competitive Rearrangement of 1,2-Dimethylcyclohexane-1,2-diols and Pinacol in the Gas Phase

system composition (Torr)[a]				reactvty ratio (**1**:pinacol)[b]	rel yields of products from **1** (%)[c]	
bulk gas (760 Torr)	$N(CH_3)_3$	**1**	pinacol		**2**	**3**
D_2		cis, 0.07	0.49	1.1	10	90
D_2	3	cis. 0.06	0.47	1.1	50	50
D_2		trans, 0.07	0.59	0.8	28	72
D_2	3	trans, 0.06	0.45	1.2	46	54
CH_4		cis. 0.07	0.51	1.3	8	92
CH_4	3	cis, 0.07	0.52	5.4	14	86
CH_4		trans, 0.06	0.46	1.2	29	71
CH_4	3	trans, 0.07	0.54	8.1	39	61

[a] All system contained 760 Torr of the bulk gas and 5 Torr of O_2. [b] Calculated by correcting the yields of rearranged products for the concentration ratio of the substrates (pinacol:**1**). [c] Standard deviation of data ca. 10%.

analysis of the intensities of each spectrum with respect to all the others.

Inspection of the data shows that the *m/z* 127 ions from *cis*-**1**, *trans*-**1**, and **2** in CH_4 and from the isobutane CI spectra of **3**, **4**, and *cis*- and *trans*-**1** give undistinguishable CID spectra, while a somewhat different spectrum is produced from **2** in $i\text{-}C_4H_{10}$.

These results suggest that the strongest acids, $C_nH_5^+$, produce from all the precursors, at the low pressures in the source of the mass spectrometer, a common structure or mixture of structures, with a predominant C_5-cyclic component. On the contrary, the adduct from the protonation of 2,2-dimethylcyclohexanone by the milder $t\text{-}C_4H_9^+$ acid retains, at least in part, its C_6-ring structure.

Under the same experimental conditions pinacol is known to undergo rearrangement into the protonated pinacone structure.[15] Furthermore, the few MH^+ ions generated from the protonation of pinacol by $t\text{-}C_4H_9^+$ and surviving in the source were shown to undergo unimolecular metastable water loss in the second FFR of the instrument.

Radiolysis. Radiolytic experiments were carried out to investigate the reaction mechanism in the high pressure range, by applying traditional mechanistic methods such as the trapping of intermediates and the isolation and analysis of their neutral end products. The composition of the reaction systems and the absolute yield of products, expressed as G_M values (number of molecules formed per 100 eV absorbed energy), as well as their isomeric distribution are reported in Table III.

Typically, the radiolytic systems contained a bulk gas, i.e., D_2, CH_4, or *neo*-C_5H_{12}, acting both as a precursor for the Brønsted acids and as a thermal bath gas, together with traces of the substrate(s), O_2 (5 Torr), used as a radicals scavenger, and $N(CH_3)_3$, when necessary. In the presence of 7 Torr of trimethylamine, the product yields depressed nearly to the detection limit, showing that their formation can be traced exclusively to ionic pathways. In fact, $N(CH_3)_3$ efficiently intercepts gaseous acids to give their conjugate bases, i.e., D_2, C_nH_4 and $i\text{-}C_4H_8$, and $N(CH_3)_3H^+$ ions. Furthermore, the isomeric composition of products was not affected by a change of the base pressure from 3 to 7 Torr.

The rearrangement reaction is a very clean one being the only process which entails observable changes of the substrates, except for the experiments involving $t\text{-}C_4H_9^+$ ions, where products from the alkylation of the diols and from addition to isobutane were also observed. The absolute yields were well reproducible within 10% from run to run.

It should be noted that the G_M values at 760 Torr account for roughly 10–20% of the gaseous Brønsted acids formed, owing to the very low concentration of the substrates in the system, limited by their vapor pressures, and to the competition by adventitious nucleophiles, either originally present as impurities or accumulated during the radiolysis. In fact, at lower pressures (100 Torr, a factor 7.6 in the partial pressure of the bulk gas) the relative yields increased to more than 80%.

Protonation of 2,2-dimethylcyclohexanone by radiolytically formed D_3^+ or $CH_5^+/C_2H_5^+$ ions in D_2 or CH_4 gave 1-acetyl-1-methylcyclopentane, suggesting the possible occurrence of product isomerization under the experimental conditions employed.

On the other hand, 1,2-dimethyl-1,2-epoxycyclohexane is too labile in the gas phase for its acid-catalyzed rearrangement to be studied, being rapidly converted to **3** (96–99% yield), without irradiating the system. By carefully washing with a base the walls of the flask before introducing the epoxide **4**, a 66% of **3** and 34% of **2** mixture was recovered after 1 h. This showed as well that **4** could not be recovered in our radiolytic systems as such, even if formed.

For the purpose of the following discussion it is worth noting that in the presence of $N(CH_3)_3$, protonation of the more tractable 1-methyl-1,2-epoxycyclohexane by the same gaseous acids employed in the present study yielded exclusively 2-methylcyclohexanone.[16]

Irradiation of systems containing either *cis*-**1** or *trans*-**1**, 760 Torr D_2 or CH_4 and up to 20 Torr H_2O, did not show any cis–trans

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epimerization occurring in competition with the pinacolic rearrangement.

Table IV gives the results of competition experiments with pinacol, used as a standard to evaluate the reactivity of the dimethylcyclohexane diols, along with the composition of the systems.

Discussion

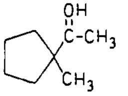
Ionization of the bulk gas and subsequent ion-molecule reactions are known to yield eventually both in mass spectrometric and in radiolytic experiments the following predominant ionic species: D_3^+ from D_2, CH_5^+ and $C_2H_5^+$ from CH_4, and t-$C_4H_9^+$ from i-C_4H_{10} or *neo*-C_5H_{12},[17,18] which all may react as Brønsted acids toward the substrates.

Although the gas-phase basicities (GB) of the glycols employed are not yet available from the literature, a rough estimate based on the known GB of their unsubstituted analogues[19,20] suggest that all the substrates should have very close $\Delta G°$ values for reaction 1, involving a given AH^+ acid. Thus, $-\Delta G°$ is expected to fall within 97–98 kcal mol^{-1} for D_3^+, 65–67 kcal mol^{-1} for CH_5^+, 36–37 kcal mol^{-1} for $C_2H_5^+$, and 4–6 kcal mol^{-1} for t-$C_4H_9^+$.

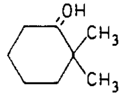
$$AH^+ + S \rightarrow A + SH^+ \qquad (1)$$

$$(A = D_2,\ CH_4/C_2H_4,\ i\text{-}C_4H_8;\ S = \text{pinacol},\ cis\text{-}\mathbf{1},\ trans\text{-}\mathbf{1})$$

Mass Spectrometric Experiments. The protonated substrates undergo extensive dehydration already in the source of the mass spectrometer. The $[MH-H_2O]^+$ species from *cis-* and *trans-***1** has the structure of protonated 1-acetyl-1-methylcyclopentane (I), ca. 5×10^{-6} s after their formation, as shown by the identity of their CID spectra with that of the m/z 127 ions from the mild protonation (t-$C_4H_9^+$) of **3** (Table II). More direct evidence is provided by the actual isolation of very high yields of **3** as neutral end product from the radiolytic experiments carried out in the absence of $N(CH_3)_3$ (Table III). Also, protonated 2,2-dimethylcyclohexanone (II), excited by the highly exoergic proton transfer in CH_4 (or D_2 at high pressure), can isomerize to I, as shown by the CID spectra and the radiolytic results. The different CID spectrum of its MH^+ ions formed in the isobutane plasma indicates, by contrast, that the retained C_6-ring structure is experimentally distinguishable from the C_5 one. The results of the epoxide **4** are to be taken with caution, due to possible isomerization of the substrate in the inlet of the instrument.



I



II

In conclusion, the low-pressure results show that all the m/z 127 ions tend to isomerize to structure I in the relatively long time scale of mass spectrometric measurements.

Radiolytic Experiments. At 760 Torr pressure, t-$C_4H_9^+$ ions, the mildest acid employed, produce only traces of **3**, indicating the existence of an energy barrier for the rearrangement of *cis-* and *trans-***1**. The results suggest that the barrier is lower along the path going to I with respect to that going to II and possibly exceeds the $\Delta G°$ value of reaction 1 with *tert*-butyl cations.

This view agrees with the isolation of the ketone **2**, retaining the original C_6-ring structure, when stronger acids like those produced in the D_2 or CH_4 radiolysis are employed, or when a lower pressure is used, which entails higher internal energy in the protonated substrate molecules undergoing pinacolic rearrangement.

In agreement with the behavior of 1,2-dimethylcyclopentane-1,2-diols,[1] no evidence for the intermediacy of a free carbenium ion could be found nor epimerization of the substrates in the presence of water was observed. Accordingly, the dehydration and the migration steps cannot be separated kinetically, and any difference among the rearrangement rates of the substrates can be traced to their original stereochemistry and to the different participating ability of the migrating groups to the water molecule loss.

The higher pressures and lower temperatures prevailing in the radiolytic experiments are expected to stabilize the MH^+ ions, and, in the presence of the strong base $N(CH_3)_3$, the protonated substrate is actually the only intermediate which can be trapped by a bimolecular reaction prior to rearrangement.

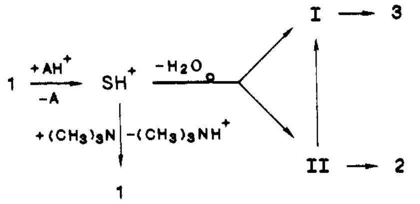
The results in fact show that $N(CH_3)_3$ (i) obviously competes with the substrate(s) for the Brønsted acids at a first level and accordingly decreases the products yield, (ii) having higher GB than the substrates, it can also deprotonate the MH^+ ions and, therefore, define a time window available to them for rearrangement, and (iii) renders deprotonation of I and II a fast process, thus inhibiting product isomerization.

Point (ii) is substantiated by the strong variation of the overall reactivity ratios (Table IV) of both *cis-* and *trans-***1** with respect to pinacol, observed in competitive experiments carried out in CH_4, with or without the base. By contrast, the very low selectivities in the absence of trimethylamine indicate that the overall reaction is essentially irreversible under the conditions employed.

Indeed, the deprotonation rate of the MH^+ species can be assumed to approach the collision rate with all protonated glycols, owing to the sufficiently large excess of the GB of $N(CH_3)_3$ over that of the substrates (24.5–25.6 kcal mol^{-1}), which sets a $k \times [B]$ value of the order of 2×10^8 s^{-1} in radiolytic systems containing 3 Torr $N(CH_3)_3$. This value falls in the proper range for the reaction to be used as a chopper capable of competition with the rearrangement, thus displaying the differences among the substrates.

Furthermore, the presence of the base increases the relative yield of **2**, which reaches the statistical 50% value when cis-**1** is protonated with the strongest acid, D_3^+. This shows that, when the internal energy of the MH^+ ions is large enough to level the rates of rearrangement of the diols and those of the competing pathways for the same substrate, the base can deprotonate II and I fast enough to suppress their isomerization. In CH_4 the same argument should apply a fortiori, owing to the lower excitation energy of the intermediates and the higher quenching efficiency of the thermal bath gas.

The experimental evidence therefore suggests the following general reaction scheme for both epimers, where SH^+ represents a mixture of protonated conformers (vide infra).



(2)

Stereochemistry of the Pinacol Rearrangement of *cis*-1,2-Dimethylcyclohexane-1,2-diol. Proton transfer to *cis*-**1** generates two possible, energetically very close structures, differing in the formal position of the proton bound to an equatorial or to an axial hydroxyl group. In the first case a ring CH_2 group and in the second a CH_3 group are anti-periplanar to the leaving water molecule and may migrate affording protonated 1-acetyl-1-methylcyclopentane (I) or 2,2-dimethylcyclohexanone (II), respectively (eq 3).

Since protonation on the two OH groups by D_3^+ or $CH_5^+/C_2H_5^+$ acids is likely to occur at nearly the same rate, the unbalance of the 2:3 products ratio in the absence of $N(CH_3)_3$ is expected to reflect product isomerization.

When the II → I pathway is inhibited by the base, the products ratio can be traced to the different rates of the parallel Wag-

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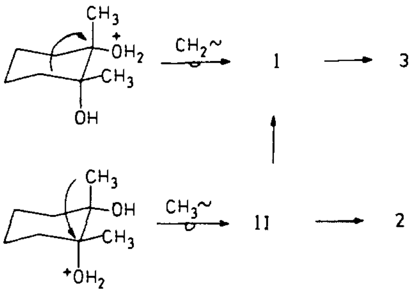
[17] Harrison, A. G. *Chemical Ionization Mass Spectrometry*; CRC Press: Boca Raton, FL 1983.

[18] Cf. Cacace, F.; Giacomello, P. *J. Am. Chem. Soc.* **1973**, *95*, 5851 and references cited therein.

[19] Cf. Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695.

[20] Cf. ref 8. The data from CAD spectra of 2,3-butanediol, *cis-*, and *trans-*1,2-cyclohexanediol were used.



(3)

ner–Meerwein-type and Nametkin-type rearrangements, both chopped by the proton-transfer reaction from the protonated conformers to $N(CH_3)_3$.

In the competitive experiments promoted by D_3^+ ions (Table IV), the isomeric composition of products from *cis*-**1** but not the reactivity ratio with respect to pinacol is influenced by the base, indicating either that the rearrangement of both substrates is much faster than proton transfer, or, more likely, that it takes place at the same rate. In fact, without discounting the difference in experimental conditions, the observation of a metastable peak corresponding to the water loss from the MH^+ ions of pinacol indicates that the rate constant of the process is roughly of the order of 10^5–10^6 s^{-1},[21] i.e., a factor 10^3–10^2 slower than proton transfer.

The statistical isomeric composition of products from cis-**1** confirms the lack of selectivity also for the same substrate, when the strong D_3^+ acid is employed.

In methane, the combination of collisional quenching of the excited intermediates and of deprotonation of the MH^+ ions by $N(CH_3)_3$ displays a remarkable difference between the rearrangement rates of pinacol and *cis*-**1**.

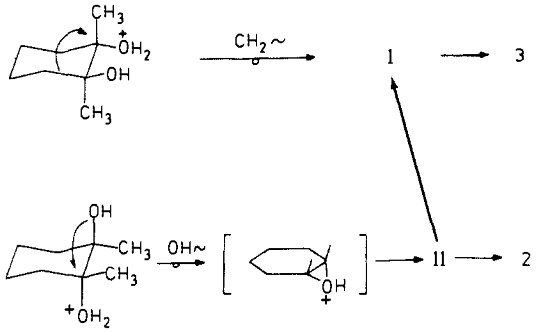
The overall process being essentially irreversible, in the absence of the base, the reactivity ratio simply reflects the proton-transfer rates to the substrate. In the presence of $N(CH_3)_3$, the specific rates of ring contraction (k_5/k_p) or methyl migration (k_6/k_p) for *cis*-**1**, relative to the rate of rearrangement of pinacol (k_p), can be estimated as a function of $k_p/k \times [B]$ (where $k \times [B]$ is the deprotonation rate of the substrates), under steady-state approximation, and assuming (i) slow ring inversion of protonated *cis*-**1** with respect to rearrangement or, equivalently, equal concentrations of the conformers and (ii) negligible isomerization of II to I. Point (i) is reasonable also in view of the buffer effect by the fast proton-transfer reaction to the base.

The almost constant trend of the relative rates, shown in Figure 1 for a reasonable range of $k_p/k \times [B]$, allows one to draw the following conclusions: methyl migration rate is ca. 1.2-fold faster in *cis*-**1** than in pinacol, despite the presence of two CH_3 in the latter substrate, while ring contraction occurs from 7.5- to 9.2-fold faster than pinacolic rearrangement, leading to a k_5/k_6 ratio of ca. 6–7 for *cis*-**1**.

Other stereochemical factors being the same in the two protonated conformers, the k_5/k_6 ratio measured in *cis*-**1** represents an estimate of the migratory aptitude of the CH_2 and CH_3 groups in the gas phase, at the range of internal energies studied in these experiments.

Stereochemistry of the Pinacol Rearrangement of *trans*-1,2-Dimethylcyclohexane-1,2-diol. Protonation of *trans*-**1** can obviously generate two possible conformers, one with both hydroxyl groups in equatorial the other in axial position (eq 4). The former cation is structurally very similar to that produced from equatorial proton transfer to *cis*-**1**, differing only by an axial instead of an equatorial methyl substituent. Accordingly, it is expected to lead to ring contraction at a rate comparable with that of the cis epimer. The axially protonated conformer, bearing both CH_3 groups in equatorial positions, but where no intramolecular hydrogen bonding is possible, can afford the protonated epoxide by backside OH participation (eq 4).

The epoxide **4** cannot be isolated as such in the system, since it was proven to give spontaneously high yields of **3** along with



(4)

small amounts of **2**. The high relative yields of **2** would not be accounted for, even if *trans*-**1** underwent pinacolic rearrangement exclusively via its axially protonated conformer, i.e., via OH participation. On the other hand, the more stable 1-methyl-1,2-epoxycyclohexane gave by protonation exclusively the corresponding C_6-ring ketone.

These observations suggest that protonated **4** undergoes isomerization to II more rapidly than proton transfer to any base in the system, and therefore the yields of **2**, measured in the presence of $N(CH_3)_3$, may well reflect the fraction of the rearrangement which takes place via hydroxyl migration.

In the absence of direct experimental evidence there is also, for *trans*-**1**, the problem of estimating the gas-phase population of the conformers.

The results reported in Table IV show that the overall reactivity ratios with respect to pinacol are sensitive even in D_2 to the presence of the base. Considering the comparable yields of **2** and **3** and the strength of the D_3^+ acid, one may assume lack of selectivity for the two parallel rearrangement channels of trans-**1**, i.e., $k_5$trans = $k_6$trans, assigning the unbalance between the isomeric products to slightly different concentrations of the equatorially and of the axially protonated forms. Under the same assumptions used for the cis epimer, a 54% population of the equatorially protonated conformer and a $k_5$trans/k_p = $k_6$trans/k_p ratio of ca. 1.5 results in D_2.

This estimate of conformers population is in fair agreement with NMR measurements in CD_2Cl_2 solution.[22]

In CH_4, an analogous treatment of the data, using the same populations, leads to the trends illustrated in Figure 1.

Therefore, ring contraction and OH participation in *trans*-**1** result to take place at comparable specific rates, which are 8–10 times faster than in the rearrangement of pinacol itself.

In this view, the rate of ring contraction of *trans*-**1** would result comparable, if slightly higher, to that of *cis*-**1** (57% of the equatorial conformer would give exactly the same value in CH_4).[23,24]

Conclusions

The course of the gas-phase pinacolic rearrangement of 1,2-dimethyl-1,2-cyclohexanediols was followed at various internal

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[21] Cf., for example: Holmes, J. L. *Org. Mass Spectrom.* **1985**, *20*, 169.

[22] The ^1H spectrum of a 0.001 M solution of *trans*-**1** in CD_2Cl_2 at 191 K (Varian XL-300) shows two separate peaks for the CH_3 at 1.10 and 1.18, whose areas correspond to 46% and 54% population of the conformers. A detailed study of the chair-to-chair equilibrium as a function of temperature is in course in our laboratory. For the purposes of the present discussion, the NMR data demonstrate that there is a very small energy difference between the conformers. Moreover the IR spectrum of a 0.01 M solution of *trans*-**1** in CCl_4, at room temperature, shows two absorption bands at 3625 and 3595 cm^{-1} (absorbance ratio 4.29) which can be assigned to the free and to the intramolecular bonded OH. This confirms the coexistence of both conformers in apolar solvents.[25]

[23] Kuhn, L. P. *J. Am. Chem. Soc.* **1952**, *74*, 2492. Cole, A. R. H.; Jefferies, P. R. *J. Chem. Soc.* **1956**, 4391.

[24] Alternatively, if one would privilege an external clock as a reference for the rearrangement, i.e., the rate of pinacol, by assuming that in D_2 k_5(trans) = k_5(cis) = k_p, then an 80% population of the equatorially protonated form and a k_6/k_p = k_6/k_5 ratio from 3.4 to 3.6 would result for *trans*-**1**. In CH_4 this would correspond to a k_5/k_p value of 5.4–6.1, a k_6/k_p value of 13.7–21.6, and a k_5/k_6 value of 0.4–0.3 for the trans epimer. In the authors' opinion the first choice is more likely, since intramolecular comparisons are generally more accurate than the intermolecular ones and, a posteriori, since the results from the second alternative appear to overestimate, especially in D_2, the participation of the hydroxyl group and to underestimate CH_2 migration rate in methane.

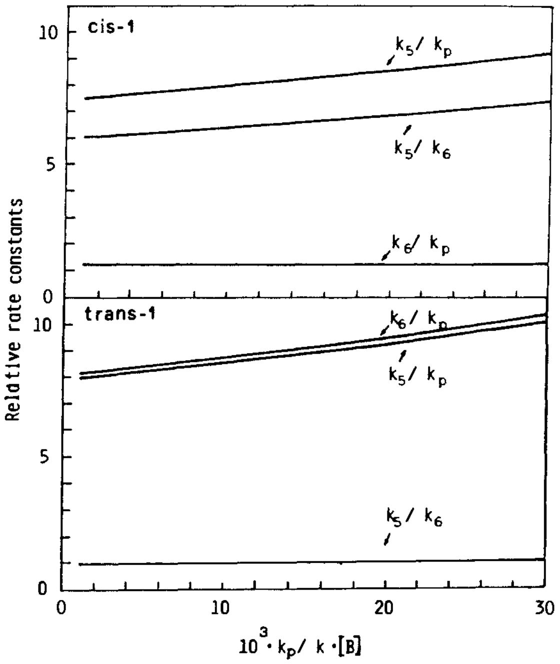

Figure 1. Calculated rate constants, relative to the one for the rearrangement of pinacol (k_p), of ring contraction (k_5), methyl, or hydroxyl migration (k_6), in *cis*- and *trans*-1,2-dimethylcyclohexane-1,2-diols as a function of the k_p/deprotonation rate ratio.

energies of the precursor ions, both by varying the nature of the acid and the pressure of the system over a wide range.

In the low-pressure regime, typical of CI mass spectrometry, the protonated epimers undergo dehydration and rearrangement, both in methane and in isobutane plasma, affording almost exclusively the protonated 1-acetyl-1-methylcyclopentane (**3**). Comparison with high-pressure radiolytic experiments, carried out in the presence of trimethylamine, indicates however that product isomerization occurred before assay by CID mass spectrometry.

At high pressure, the rearrangement promoted by the D_3^+ acid displayed no selectivity among the substrates nor between the possible group-migration paths. Furthermore the base had barely detectable effects on the relative rearrangement rates.

This indicates that differences in the energy barriers associated with different stereochemical situations of the rearranging substrates cannot be appreciated, owing to the high internal energy imparted by the protonation step and to the low efficiency of the thermalyzing bath gas. Nevertheless, D_3^+ experiment proved extremely useful to evaluate the population of the conformers of the reacting diols.

Use of the acids mixture from the high-pressure ionization of methane realized the experimental conditions suited to exploit the trapping reaction of the intermediates by trimethylamine and allowed us to compare the migration rates of the $-CH_2$, CH_3, and OH groups as well as to verify the stereochemical requirements of the pinacolic rearrangement in the absence of strong solvation interactions.

The observed trend $k_6(\text{trans}) \simeq k_5(\text{trans}) \geq k_5(\text{cis}) > k_6(\text{cis}) \geq k_p$ shows that OH participation in the trans epimer occurs at approximately the same rate as ring contraction, which, in turn, is a little faster than in *cis*-**1**; the steric repulsion of two axial methyl groups in *trans*-**1**, against the one in the cis epimer, may explain the difference.

Methyl migration rate in *cis*-1,2-cyclopentanediol is comparable with that in pinacol[1] and therefore somewhat slower than in *cis*-**1**. This indicates that the steric strain arising by two eclipsed methyl groups, partly balanced by a stronger intramolecular hydrogen bond,[23] does not accelerate the rearrangement which, instead, is favored by a better anti-periplanar configuration.

The results indicate as well that the gas-phase rearrangement of pinacol itself, bearing four methyl groups, is likely to proceed via a more complex mechanism, whose rate is heavily influenced by the hindered rotation around the carbon–carbon bond.

From a more general standpoint, a comparison of the magnitude of unimolecular rearrangement rate constants with the deprotonation rate suggests that the intermediates undergo a sufficient number of collisions with methane molecules for the reaction to be thermal. The explanation for the relative inefficiency of the process in neopentane at high pressure is rather to be sought in some specific interactions with the environment, which stabilize the intermediates against isomerization. A possibility, which however deserves further investigation, may be an incipient solvation by isobutene, the conjugate base of the gaseous acid whose local concentration is initially very high.

On the other hand, the enhanced role of intramolecular factors on the reaction mechanism in the disperse gas state is stressed by a comparison with solution results. In 1 M $HClO_4$ at 59.7 °C, participation of the migrating group to the breaking of the carbon–oxygen bond was unimportant, and the calculated rate constants for the process were 4.2×10^{-5}, 1.2×10^{-5}, and 1.5×10^{-5} s^{-1} for *trans*-**1**, *cis*-**1**, and pinacol, respectively.[3,25] Here the solvent plays a dominating mechanistic role, and, interestingly enough, the absolute rates for the rearrangement fall by many orders of magnitude with respect to the gas state. Even the chair-to-chair ring inversion of *trans*-**1**, very fast in solution, appears to be a slow process when compared to the pinacol rearrangement in the gas phase.

In conclusion, the results of the present work show once more how deeply interactions with the medium may affect mechanism and underline the potential of high-pressure gas-phase chemistry as a tool for investigating the crucial transition belt, where solvation phenomena determine the evolution of the reaction intermediates. This appears particularly relevant when thermal unimolecular processes, like isomerizations, etc., are involved.

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Registry No. *cis*-**1**, 33046-21-8; *trans*-**1**, 33046-22-9; **2**, 1193-47-1; **3**, 13388-93-7; **4**, 17612-36-1; D_2, 7782-39-0; CH_4, 74-82-8; CMe_4, 463-82-1; D_3^+, 12595-96-9; CH_5^+, 15135-49-6; Et^+, 14936-94-8; *i*-C_4H_{10}, 115-11-7; Me_3C^+, 14804-25-2; NMe_3, 75-50-3; 1,2-dimethylcyclohexene, 1674-10-8; 2-methylcyclohexanone, 583-60-8.

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[25] Bunton, C. A.; Carr, M. D. *J. Chem. Soc.* **1963**, 5861.